

# Reverse polarity optical-OFDM (RPO-OFDM): dimming compatible OFDM for gigabit VLC links

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**Abstract:** Visible light communications (VLC) technology permits the exploitation of light-emitting diode (LED) luminaries for simultaneous illumination and broadband wireless communication. Optical orthogonal frequency-division multiplexing (O-OFDM) is a promising modulation technique for VLC systems, in which the real-valued O-OFDM baseband signal is used to modulate the instantaneous power of the optical carrier to achieve gigabit data rates. However, a major design challenge that limits the commercialization of VLC is how to incorporate the industry-preferred pulse-width modulation (PWM) light dimming technique while maintaining a broadband and reliable communication link. In this work, a novel signal format, reverse polarity O-OFDM (RPO-OFDM), is proposed to combine the fast O-OFDM communication signal with the relatively slow PWM dimming signal, where both signals contribute to the effective LED brightness. The advantages of using RPO-OFDM include, (1) the data rate is not limited by the frequency of the PWM signal, (2) the LED dynamic range is fully utilized to minimize the nonlinear distortion of the O-OFDM communication signal, and (3) the bit-error performance is sustained over a large fraction of the luminaire dimming range. In addition, RPO-OFDM offers a practical approach to utilize off-the-shelf LED drivers. We show results of numerical simulations to study the trade-offs between the PWM duty cycle, average electrical O-OFDM signal power, radiated optical flux as well as human perceived light.

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## 1. Introduction

Advances in solid-state lighting (SSL) are enabling LEDs to be the primary illumination source of the future [1]. The adoption of LEDs aims to significantly reduce energy consumption and facilitate precise intensity and color control of illuminated spaces [2]. Two methods are generally utilized to produce the white light in LED-based luminaries [3]. The cheapest and most popular is phosphor conversion, in which a blue LED is coated with phosphor to emit broad-spectrum white light. The second approach offers color-tunable lighting through combining monochromatic LEDs of different colors to produce white, *i.e.* color mixing. Besides the several advantages of LEDs, they also have a fast response time making them excellent light sources for high-speed VLC links in which data is transmitted wirelessly from LED-based luminaries through subtle intensity variations [4]. In VLC systems, the communication signal is simply modulated onto the instantaneous power of the optical carrier and the optical detector generates a current proportional to the received instantaneous power, *i.e.*, intensity modulation with direct detection (IM/DD) [5]. VLC is motivated by several benefits including a huge, unregulated bandwidth (THz), license-free operation, no interference with RF systems, low-cost front-ends, and no health concerns, assuming compliance with eye safety regulations. Due to the potential synergy of indoor lighting and communication, it is unsurprising that VLC is gaining attention in academia and industry as a complementary to radio frequency (RF) technology [6], *i.e.* based on existing power-line infrastructure [7].

VLC research to date has primarily been focused on achieving increasingly high data rates [8, 9]. The spectrally-efficient O-OFDM is attractive to overcome the limited LED modulation bandwidth, thus constitutes a hot research topic in the field of VLC [10]. In O-OFDM based VLC systems, high data rates are supported through parallel transmission of high-order multilevel quadrature amplitude modulation (M-QAM) symbols on orthogonal sub-carriers.

Assuming near-field communication in a static scenario, recent experimental setups have been demonstrated to achieve Gbps VLC links using commercial off-the-shelf components [11]. According to the laboratory conditions of these demonstrations, the human factors component and illumination features for a realistic illumination and communication system have been largely overlooked. Such research is vital to the adoption of VLC. For example, dimming is an essential feature in lighting to meet the functional and aesthetic requirements of a space as well as to conserve energy [12]. Additionally, a dimmed lamp produces less heat, extending the lifespan of LED light sources and reducing HVAC cooling loads. Paramount to the practical challenges of VLC is ensuring dimming functionality while maintaining a reliable broadband communication link. In the literature, to our knowledge, demonstrating the illumination compatibility with high-speed communication remains an open challenge.

Recent research efforts are conducted to assist in developing modulation techniques which address the challenge of incorporating broadband VLC with high-quality illumination and lighting state control. In [13], time-domain O-OFDM symbols are transmitted onto the PWM signal only during the "on-state". Here the data throughput is limited to the relatively low PWM line rate. In [14], the LED drive current is the time-domain O-OFDM signal multiplied by a periodic PWM pulse train. Here the practical communication is only feasible when the PWM signal is at least twice the frequency assigned to the largest O-OFDM sub-carrier frequency, *i.e.* inter-carrier interference (ICI) for slower PWM rates. This constraint diminishes the feasibility of industry compatible dimmed broadband VLC link as PWM frequencies of off-the-shelf LED drivers are in KHz.

In contrast, our work proposes a novel approach (1) to utilize the entire PWM cycle for data transmission instead of limiting the transmission to be only during the "on-state", *i.e.*, the data throughput is not limited by the PWM frequency, (2) to use the full LED dynamic range of operation to minimize the nonlinear distortion (mainly clipping) of the O-OFDM signal, *i.e.*, DC biasing is not required and the linear range of operation is extended, and (3) to maintain a high link capacity for a wide dimming range, *i.e.* the signal-to-noise ratio (SNR) is independent on the dimming level within that wide range.

The remainder of this paper is organized as follows. PWM dimming and two versions of the O-OFDM baseband signal are highlighted in Section 2. The proposed RPO-OFDM is introduced in Section 3. In Section 4, the signal quality and perceived brightness are covered. The achieved system performance based on simulation results and relating to different system parameters is presented in Section 5. Conclusions are drawn in Section 6.

## 2. Dimming and O-OFDM modulation

Lighting controls can increase the value of buildings by making them more productive, comfortable, and energy efficient. This is often a product of dimming functionality that is application specific. For instance, settings such as conference rooms, office rooms or examination rooms, can require light levels as low as 1% percent of maximum illumination for aesthetic and comfort purposes. The brightness of an LED is adjusted by controlling the forward current through the LED. There are mainly two possible methods to dim LEDs: (1) analog dimming and (2) digital dimming. Analog dimming, also known as amplitude modulation (AM) or continuous current reduction (CCR), is the simplest type of dimming control. This technique lessens the current amplitude linearly to adjust the radiated optical flux. In digital dimming, the average duty cycle represents the equivalent analog dimming level, *i.e.* a digitally modulated pulse train drives the LED at a constant current level. Pulse width modulation (PWM) is the simplest example of digital dimming modulation techniques. The time period of the PWM signal is fixed, whereas the duty cycle  $D$  varies proportionally to the required dimming percentage. Since PWM reduces light intensity more linearly than AM and induces less of a chromaticity shift, PWM is

preferred in industry solutions [15].

A PWM signal current  $i_{PWM}(t)$  with pulse width  $T$  and period  $T_{PWM}$  is shown in Fig. 1 and can be expressed as,

$$i_{PWM}(t) = \begin{cases} I_H, & 0 \leq t < T \\ I_L, & T < t \leq T_{PWM} \end{cases} \quad (1)$$

where  $I_H$  is the high level "on-state" LED current,  $I_L$  is the low level "off-state" LED current and  $D = T/T_{PWM}$ .

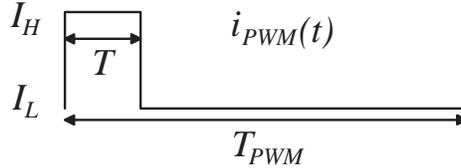


Fig. 1. The PWM signal.

Asymmetrically clipped optical OFDM (ACO-OFDM) and DC biased optical OFDM (DCO-OFDM) are well known IM forms of O-OFDM [16]. Both are very similar to RF-OFDM, but they have their own requirements and methods. The Inverse Fast Fourier Transform (IFFT) operation modulates the O-OFDM sub-carriers and generates the time-domain signal. A real O-OFDM signal can be generated by constraining the input to the IFFT operation to have Hermitian symmetry, *i.e.*  $S_n = S_{N-n}^*$ . In ACO-OFDM, the generated bipolar signal is converted to unipolar through clipping of all negative values at zero. In DCO-OFDM, the generated bipolar time-domain signal is used to modulate the optical carrier intensity after DC biasing of the LED. To demonstrate the proposed approach, the ACO-OFDM signal format is considered. The generated time-domain ACO-OFDM current samples and signal current can be mathematically described as follows:

$$i_k = \sum_{n=0}^{N-1} S_n \exp(j \frac{2\pi}{N} nk) \quad (2)$$

$$i_{OFDM}(t) = \sum_{n=0}^{N-1} S_n \exp(j\omega_n t), 0 \leq t < T_{OFDM} \quad (3)$$

where, the values  $S_n, n = 0, \dots, N-1$  are the input data symbols of the  $n^{th}$  sub-carrier,  $i_k, k = 0, \dots, N-1$  are the  $N$  time-domain output current samples,  $i_{OFDM}(t)$  is the O-OFDM time-domain signal current,  $T_{OFDM}$  is the time-domain O-OFDM symbol period, and  $\omega_n = 2\pi n/T_{OFDM}$ . A normalized ACO-OFDM time-domain symbol is also shown in Fig. 2.

Unsurprisingly, dimming presents a number of immediate challenges to VLC. By its very nature, dimming reduces the average signal strength. It also places extra constraints on the O-OFDM modulation scheme which must enable both data transmission and light intensity adjustment. In the context of these problems, an intensity control approach is proposed to achieve optimal data rates without sacrificing illumination features as well as quality.

### 3. The proposed RPO-OFDM

In this work, it is proposed to combine  $i_{OFDM}(t)$  with  $i_{PWM}(t)$  as follows:

$$i_{LED}(t) = \begin{cases} i_{PWM}(t) - m \times i_{OFDM}(t), & 0 \leq t \leq T \\ i_{PWM}(t) + m \times i_{OFDM}(t), & T < t \leq T_{PWM} \end{cases} \quad (4)$$

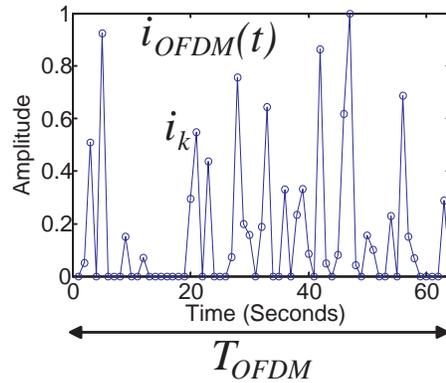


Fig. 2. The unipolar ACO-OFDM symbol. The circles represent the different current samples of the ACO-OFDM symbol and the solid blue line represents the analog ACO-OFDM signal current ( $i_{OFDM}(t)$ ) after a digital-to-analog conversion.

where,  $i_{LED}(t)$  is the LED drive current and  $m$  is a real-valued scaling factor of the O-OFDM modulating signal, *i.e.* sets the average electrical O-OFDM signal power  $P_{OFDM}$ .

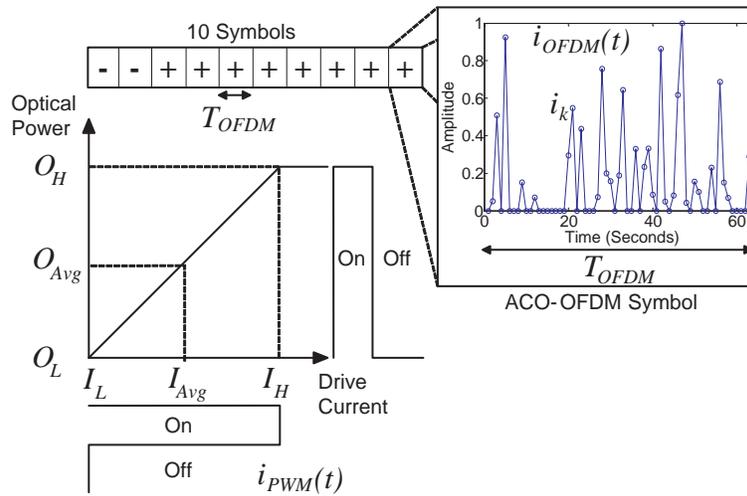


Fig. 3. An example to demonstrate the proposed RPO-OFDM system: based on the dimming level, *i.e.*  $D$ , the polarity of the O-OFDM symbols are adjusted before the O-OFDM signal is superimposed on the PWM signal. The non-linear transfer function of the LED:  $O_L$  denotes the output optical power corresponding to the input current  $I_L$  and  $O_H$  denotes the output optical power corresponding to the input current  $I_H$ .

The LED non-linear transfer function and the proposed system with an example are illustrated in Fig. 3. The non-linear transfer function relates the input LED drive current to the output optical power. The emitted optical power of a  $i_{PWM}(t)$  pulsating between  $I_L$  and  $I_H$  is shown.  $I_H$  is assumed to correspond to the maximum allowed  $i_{LED}(t)$  and  $I_L$  corresponds to the minimum  $i_{LED}(t)$  according to the LED data sheet, *i.e.* the LED dynamic range can be denoted by  $I_H - I_L$ . In the proposed system,  $i_{OFDM}(t)$  is superimposed on  $i_{PWM}(t)$  after setting a proper

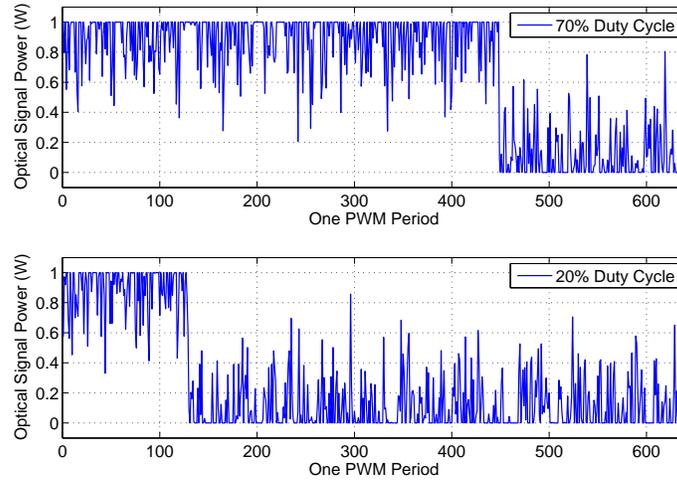


Fig. 4. Optical RPO-OFDM signal waveform based on ACO-OFDM at 70%  $D$  (upper) and 20%  $D$  (lower).  $I_H = 1A$ ,  $I_L = 0A$ , 8-QAM and  $P_{OFDM} = 16dBm$ .

polarity of the individual ACO-OFDM symbols using a RPO-OFDM modulator depending on whether the symbol is being transmitted on  $I_H$  or  $I_L$  during  $T_{PWM}$ . To explain the idea of RPO-OFDM with an example,  $D = 20\%$ , 10 ACO-OFDM symbols,  $i_k = 64$  and  $T_{PWM} = 10 \times T_{OFDM}$  are assumed. Consequently, the polarity of the first two ACO-OFDM symbols is reversed, *i.e.* -ve polarity, then transmitted on the  $I_H$  followed by 8 ACO-OFDM symbols, *i.e.* +ve polarity, transmitted on  $I_L$ . At the receiver side, and after time-synchronization, all 640 samples are extracted and the polarity of the first 128 samples is re-adjusted. Figure 4 shows ACO-OFDM symbols that are sequentially transmitted at  $D = 20\%$  and  $D = 70\%$ .

The building blocks of the RPO-OFDM modulator are shown in Fig. 5. The serial data bits are grouped into symbols and modulated using a QAM modulator. The mapper assigns the symbols to the IFFT input bins (sub-carriers). The O-OFDM symbol is assembled in frequency domain and the O-OFDM time domain signal is obtained using the IFFT operation. Based on how the symbols are assigned to the sub-carriers, the unipolar operation forms unipolar O-OFDM symbols such as the operation used to generate the ACO-OFDM [16], the Flip-OFDM [17], the position modulation OFDM (PM-OFDM) [18] or the unipolar OFDM (U-OFDM) [19]. A fixed length cyclic prefix (CP) (to avoid any inter-symbol interference (ISI)) is added before the polarity inverter. Based on the target dimming level, *i.e.*  $D$ , the polarity inverter is activated.

As shown in Fig. 6(a), the proposed approach considers, for example, modulating the dimming signal current  $i_{PWM}(t)$  supplied by the LED driver (assuming PWM as shown in Fig. 6(b)) using the polarity-adjusted O-OFDM analog signal current ( $i_{OFDM}(t)$ ) available after the RPO-OFDM modulator according to a dimming set point, *i.e.*  $D$ . There are different circuit topologies to combine  $i_{PWM}(t)$  and  $i_{OFDM}(t)$  to obtain  $i_{LED}(t)$ . It is also possible to realize a circuit topology to directly drive the LED using  $i_{OFDM}(t)$  (see Fig. 6(c)). However, these topics are not the scope of the paper and will be shown in a latter work. It is also worth pointing out that RPO-OFDM can also be applied to any unipolar O-OFDM version or the bipolar O-OFDM version, *i.e.* DCO-OFDM. For example, the same modulation-demodulation sequence is valid for a bipolar DCO-OFDM, however using two consecutive PWM periods.

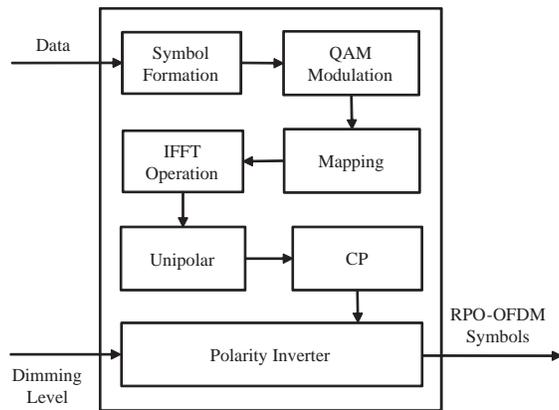


Fig. 5. Building blocks of the RPO-OFDM generator.

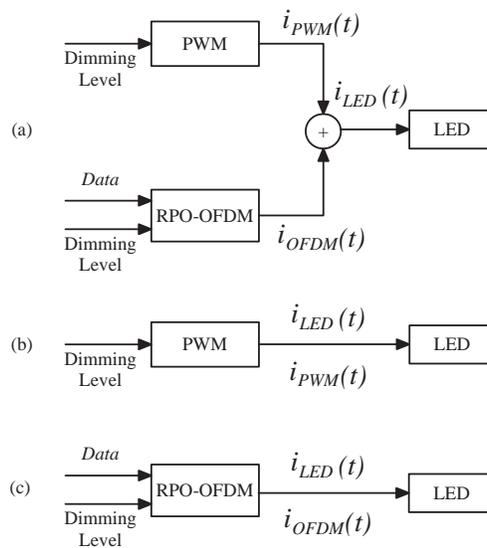


Fig. 6. (a) modulating the dimming signal current  $i_{PWM}(t)$  using the polarity-adjusted O-OFDM analog signal current  $i_{OFDM}(t)$ . (b) PWM dimming without RPO-OFDM VLC. (c) directly drive the LED using  $i_{OFDM}(t)$ .

#### 4. Signal quality and perceived brightness

In terms of spectral efficiency and bit-error performance, the proposed approach based on PWM offers several advantages over AM. Using AM, the ACO-OFDM signal is superimposed on a fixed bias level. The consequences are reduced LED dynamic range for transmission, the ACO-OFDM signal power has to be optimized for each bias level and the performance is directly related to the dimming set-point. However, in the proposed approach, and assuming that the PWM signal is utilizing the full LED dynamic range, the ACO-OFDM signal clipping is avoided for a wider amplitude-range of OFDM samples, *i.e.* the transmitted OFDM signal shape is preserved. Preserving the OFDM signal shape corresponds to less induced clipping noise allowing the use of high-order constellations (better spectral efficiency) or the establishment of more robust links (better BER). The proposed approach decouples dimming for a wide-range from the performance, *i.e.* assuming optimum ACO-OFDM signal power to maintain a target quality of service (QoS).

The SNR for each scaled ACO-OFDM symbol is the ratio between the power of the undistorted part of the signal and noise power and can be expressed as,

$$SNR \propto \frac{\sigma_{LED}^2}{\sigma_N^2} \propto \frac{m^2 \sigma_{OFDM}^2}{\sigma_N^2} \quad (5)$$

where,  $\sigma_{LED}^2$  denotes the LED current variance and  $\sigma_N^2$  denotes variance of the additive white Gaussian noise (AWGN) representing shot and thermal noise. Any DC optical power component or increase in  $D$  does not contribute to SNR improvement. The SNR can be improved only through maximizing  $\sigma_{LED}^2$ , *i.e.* maximum  $P_{OFDM}$  determined by the value of the scaling factor  $m$ . However, to ensure that  $i_k$  stays within the dynamic range of the LED, a maximum  $m$  with absolute value of  $I_H / \max(i_k)$  is required. At a certain  $P_{OFDM}$ , If the magnitude of any  $i_k$  sample is beyond the dynamic range of the LED, and assuming  $I_L = 0$ ,  $i_{LED}(t)$  will be clipped and the clipped signal  $i'_{LED}(t)$  is given by

$$i'_{LED}(t) = \begin{cases} 0, & i_k \geq I_H \text{ (on-state)} \\ i_{LED}(t), & i_k < I_H \\ I_H, & i_k \geq I_H \text{ (off-state)} \end{cases} \quad (6)$$

For such clipped signal, the SNR is calculated again using the ratio between the power of the undistorted part of the signal and the effective noise power, which now accounts for contributions caused by shot and thermal noise as well as induced clipping noise.

As shown previously in Fig. 3, the average optical power denoted by  $O_{Avg}$  can be controlled by adjusting  $D$  or jointly adjusting  $D$  and  $m$ . An optimum  $m$  is determined based on the available LED dynamic range, the target dimming range and the M-QAM order. Over one PWM period,  $O_{Avg}$  corresponds to an average LED current denoted by  $I_{Avg}$  and described as,

$$I_{Avg} = D(I_H - \frac{mi}{N} \sum_{k=0}^{N-1} i_k) + (1-D)(I_L + \frac{mj}{N} \sum_{k=0}^{N-1} i_k) \quad (7)$$

where,  $i$  is the number of the O-OFDM symbols transmitted during the "on-state" and  $j$  is the number of the O-OFDM symbols transmitted during the "off-state". Assuming the LED input-output characteristic as shown in Fig. 3,  $I_L = 0$  and  $D = 50\%$ , it is clearly observed that  $I_{Avg}$  is always equal to half the  $I_H$  and independent on  $m$ , *i.e.*  $P_{OFDM}$ .

As for brightness, the human eye responds to lower  $O_{Avg}$  by enlarging the pupil, allowing more light to enter the eye. This response results in a non-linear relation between measured and perceived light levels that is captured by the following formula:

$$Perceived\ Light\ (\%) = 100 * \sqrt{\frac{Measured\ Light\ (\%)}{100}} \quad (8)$$

## 5. Simulation results

Simulations are conducted to investigate the influence of  $D$  and  $P_{OFDM}$  on the radiated optical power, *i.e.* optical dimming, as well as the perceived LED brightness, *i.e.* perceived dimming. The dimming level is defined as a percentage of the maximum brightness, *i.e.* 100% dimming is full brightness.  $I_H = 1A$ ,  $I_L = 0A$  and  $P_{OFDM}$  are calculated over one ACO-OFDM symbol. Modulating signal current values above 1A are clipped. Figure 7 shows the obtained optical dimming and perceived dimming as a function of  $D$ . Curves are obtained at different values of  $P_{OFDM}$  that is incremented starting 10dBm up to 24dBm in steps of 2dBm. The numerical results confirm that the optical dimming can be linearly adjusted by varying  $D$  for different values of  $P_{OFDM}$ . The O-OFDM signal is the sum of  $N$  independent sub-carriers. For large values of  $N$  ( $N > 10$ ), the ACO-OFDM envelope can be accurately modeled as a Gaussian random process (due to the central limit theorem) with zero mean. Thus at  $D = 50\%$ ,  $P_{OFDM}$  has no effect on the dimming level. It is also highlighted that the human eye has better sensitivity at low luminance than high luminance. The non-linear relation between optical dimming and perceived dimming is clearly observed. For instance, decreasing the optical power by 50% achieves only a 70% reduction in brightness.

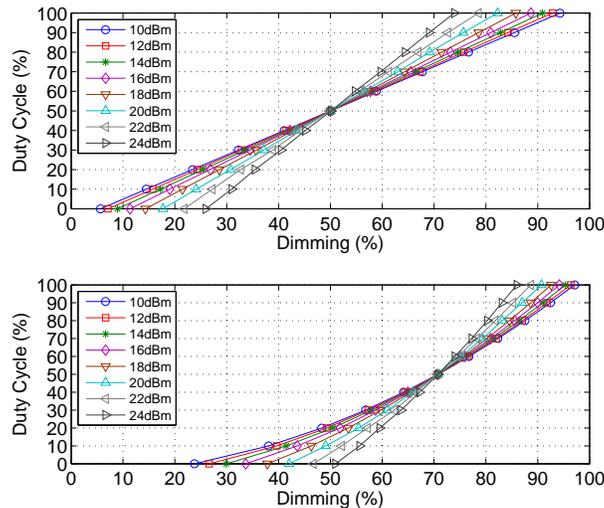


Fig. 7. Optical dimming (upper) and perceived dimming (lower) as a function of  $D$  and  $P_{OFDM}$ .

Figure 8 illustrates how the dimming range decreases as  $P_{OFDM}$  increases. At any  $P_{OFDM}$  value, the range between the two vertical circles represents the optical dimming range, however the range between the two vertical squares represents the perceived dimming range. For low  $P_{OFDM}$ , *e.g.* at  $P_{OFDM} = 10dBm$ , the full dimming range is slightly reduced by 10%, *i.e.* from 95% up to 5%. At  $P_{OFDM} = 16dBm$ , the highest brightness level that can be achieved is limited to 90% and the highest dimming level that can be reached is 10%. Further increase of  $P_{OFDM}$  narrows the dimming range around 50% dimming.

The influence of  $P_{OFDM}$  on the system bit-error performance is also investigated. In these Monte-carlo simulations, un-coded 8-QAM, 16-QAM, and 32-QAM modulation schemes, -3dBm AWGN,  $I_H = 1A$ ,  $I_L = 0A$  and perfect synchronization between the transmitter and the receiver are assumed. Typical receiver sensitivity is around -30dBm, however a high AWGN

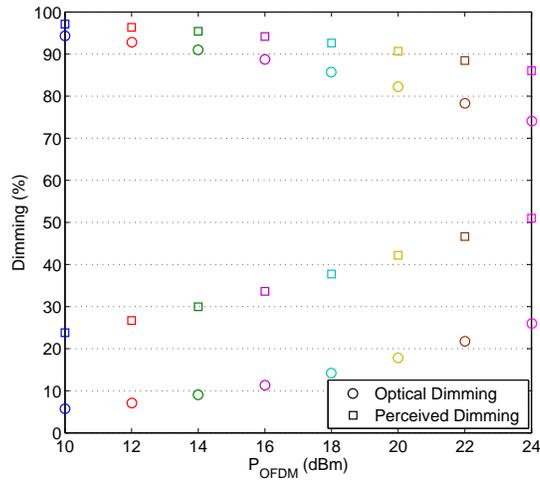


Fig. 8. The influence of  $P_{OFDM}$  on the achieved optical dimming and perceived dimming ranges.

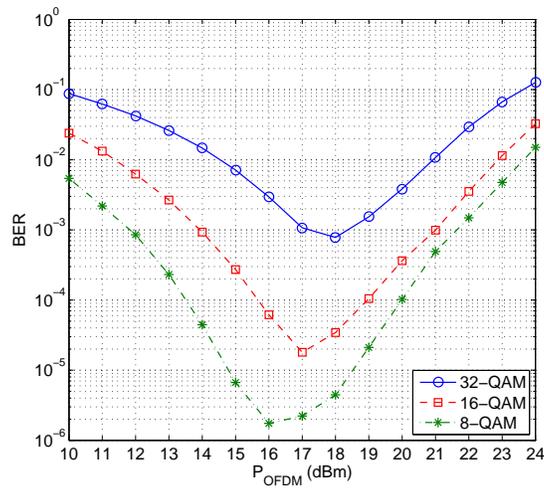


Fig. 9. Bit-error performance as a function of  $P_{OFDM}$  for un-coded 8-QAM, 16-QAM, and 32-QAM modulation schemes.

value, *i.e.* -3dBm, is chosen in order to be able to illustrate the full behavior of the bit-error ratio (BER) curves, *i.e.* avoid BER values below  $10^{-6}$  that are difficult to obtain using simulations. For a target BER of  $10^{-3}$ , it is clearly confirmed that for all three curves,  $P_{OFDM} = 10dBm$  is not sufficient to achieve the target BER. Above 14dBm and below 21dBm, 8-QAM and 16-QAM curves show BER values better than  $10^{-3}$ . However, for wider dimming range  $P_s = 14dBm$  is recommended as illustrated in Fig. 8. To achieve BER of  $10^{-3}$  using 32-QAM,  $P_{OFDM}$  must be set at 18dBm. The SNR and BER are improved, as expected, with the increase of  $P_{OFDM}$  reaching an optimal value for a specific noise power. By further increasing  $P_{OFDM}$ , the SNR starts to deteriorate as a result of induced non-linear distortions caused by the LED limited

dynamic range (clipping at 1A), *i.e.* AWGN noise dominates at low  $P_{OFDM}$  values and clipping distortion dominates at high  $P_{OFDM}$  values. The optimum  $P_{OFDM}$  values for 8-QAM, 16-QAM, and 32-QAM are 16dBm, 17dBm and 18dBm, respectively.

A VLC enabled lighting design must carefully consider to meet the challenge of providing a lighting plan that acknowledges the unique qualities and services of individual spaces and applications. Using Fig. 8 and Fig. 9 (having the same  $x$ -axis), for example, at 8-QAM, the lowest BER of  $10^{-6}$  is achieved at  $P_{OFDM} = 16dBm$  and is maintained independent on the dimming range that is between 90% and 10%. However, BER of  $10^{-3}$ , requires only  $P_{OFDM} = 12dBm$  and is maintained independent on the dimming range that is between 92% and 7%. Thus  $P_{OFDM}$  has to be optimized for maximum data-rate, minimum BER and/or target dimming range.

For a target BER of  $10^{-3}$  and AWGN of -3dBm, Fig. 10 shows the possible modulation order as a function of the optical dimming as well as the perceived dimming. It is clearly noticed how a wide dimming range of operation is supported, *i.e.* between 88% and 12% for optical dimming and between 93% and 35% for perceived dimming, while maintaining 32-QAM, *i.e.* high order modulation corresponds to high spectral efficiency. Beyond this range, *e.g.* 8-QAM, is maintained between 93% and 7% for optical dimming and between 97% and 26% for perceived dimming.

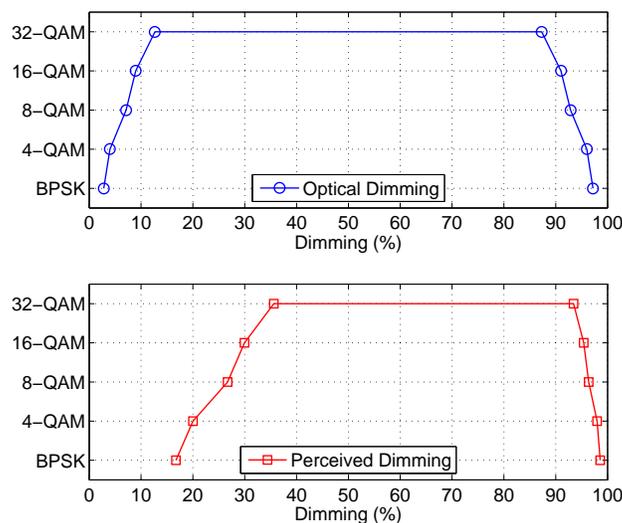


Fig. 10. Modulation order vs. optical dimming (upper) and perceived dimming (lower).

Finally, Fig. 11 clearly shows the corresponding dimming range at optimum values of  $P_{OFDM}$  for 8-QAM, 16-QAM, and 32-QAM. For example, using  $P_{OFDM} = 18dBm$  jointly maximizes the spectral efficiency, *i.e.* 32-QAM, and minimizes the BER, *i.e.* about  $10^{-3}$ . This BER is maintained independent on the dimming range that is between 87% and 14%. The dimming range can be extended by reducing  $P_{OFDM}$  (loss in BER) up to 1dB ( $P_{OFDM} = 17dBm$ ) while maintaining  $BER = 10^{-3}$ . To further extend the dimming range, a switch to 16-QAM (loss in spectral efficiency) is required. Using 16-QAM, the dimming range can be further extended by reducing  $P_{OFDM}$  up to 3dB ( $P_{OFDM} = 14dBm$ ) while maintaining BER below  $10^{-3}$ . The corresponding values of  $D$  to obtain certain dimming set-points at different values of  $P_{OFDM}$  are shown in Fig. 7. Using Fig. 11 and Fig. 7 (having the same  $x$ -axis), for example, at optimum

$P_{OFDM}$ ,  $D = 8\%$  and  $D = 12\%$  are required to obtain 20% optical dimming for 32-QAM and 16-QAM, respectively.

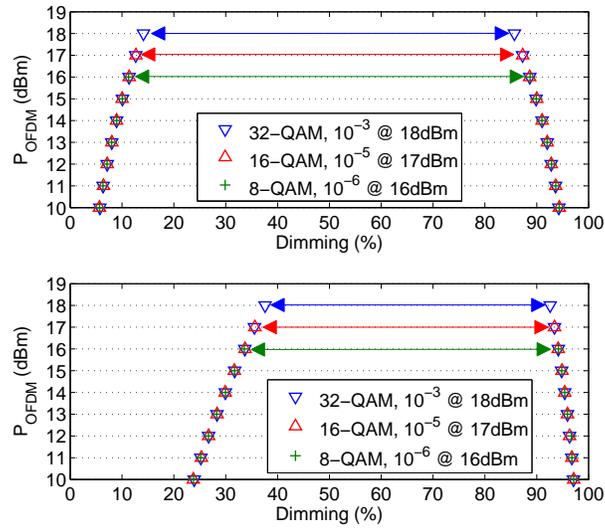


Fig. 11.  $P_{OFDM}$  vs. optical dimming (upper) and perceived dimming (lower).

## 6. Conclusion

Our numerical simulations show that the proposed RPO-OFDM and dimming/communication signals combination algorithm demonstrate the viability of achieving both dimming and high data rate goals across a wide range of intensity settings while preserving compliance with industry-standard dimming techniques. High data rates promised by O-OFDM modulation can be maintained while offering a wide dimming range to serve illumination and/or energy saving goals. In RPO-OFDM, when a room is to be dimly lit, the communication capacity does not need to be reduced proportional to intensity. The BER performance can be significantly improved because the proposed algorithm utilizes the full dynamic range of an LED and eliminates the need to adaptively adjust the LED operating point, *i.e.* DC bias, to maximize the dimming range while maintaining a good SNR to fulfill a target data rate. We anticipate describing implementation details of how the PWM and RPO-OFDM will be achieved in practical systems in future works.

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